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DISCUSSION OF STRUCTURAL DAMPING IN SUSPENSION BRIDGES

(Published in March, 1951)

By R. K. Bernhard, George S. Vincent, F. B. Farquharson, Arne Selberg, and the Late Friedrich Bleich and L. W. Teller

STRUCTURAL DIVISION

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DISCUSSION

R. K. Bernhard,[4] M. ASCE.—In their paper the authors determined experimentally the logarithmic damping decrement of steel structures by means of displacement amplitude-decay curves. They obtained a maximum value of 0.291 for the logarithmic damping decrement (Fig. 16, curve for $f_n =$ 210 lb) in a bolted truss with a span of 36.83 ft.

It might be of interest to compare this figure with values obtained by another method based on response curves produced by means of mechanical oscillators.[5] These experiments yielded values for the logarithmic damping decrement up to 0.31, hence maximum values that are only 6.5% higher than those mentioned. This slight increase might be explained as follows:

1. The response curve experiments were carried out under actual field condition on bridges with substantially larger spans.
2. The values for the logarithmic damping decrement obtained from field tests included the damping due to the bearings, supports, foundations, surrounding soil, and other such factors.

Furthermore, the statement of the authors that friction in riveted connections—as compared for example with quasi-frictionless welded connections—increases the friction damping substantially agrees with experiments of the writer.[6]

Finally, similarly to the findings of the authors, periodic field tests with oscillators showed that the tightness of the rivets has a rather significant influence on the damping characteristics. Since riveted connections of newly installed structures are normally in a tighter condition than older, worn-out structures, a decrease in the logarithmic damping decrement has been observed with aging (retrogression period). However, a slight increase in damping during the first years (training period) of riveted bridges, probably due to a working-in procedure, could also be established.[6]

It is indeed gratifying that the laboratory experiments, which could be carried out more rigorously than the writer's field tests, did lead to similar conclusions. The authors are to be congratulated for their valuable contribution in this much neglected field of mechanical vibrations.

George S. Vincent,[7] M. ASCE.—A compact, well-coordinated presentation of theory and experimental data on the problem of damping in suspension bridges, a problem distinctly different from that of damping in other types of

Note.—This paper by the Late Friedrich Bleich and L. W. Teller was published in March, 1951, as *Proceedings-Separate No. 61*. The numbering of footnotes, equations, and illustrations in this Separate is a continuation of the consecutive numbering used in the original paper.

[4] Prof., Eng. Mechanics, Rutgers Univ., New Brunswick, N. J.

[5] "Dynamic Test by Means of Induced Vibrations," by Rudolf K. Bernhard, *Proceedings*, American Society for Testing Materials, Vol. 37, Part II, 1937, p. 634.

[6] "Artificial Vibrations—A New Method of Research," by Rudolf K. Bernhard, *Civil Engineering*, Vol. 7, 1937, pp. 286–287.

[7] Principal Highway Bridge Engr., U. S. Bureau of Public Roads, Structural Research Laboratory, Univ. of Washington, Seattle, Wash.

structures, is given in this paper. The mathematical treatment is surprisingly simple and direct, and the report of tests is packed with facts, the significance of which is well-accented in the section titled "Summary of Indication from the Damping Tests." This summary and the correlation presented in Part III of the paper leave little to be added by way of interpretation of results of the study.

The data given on atmospheric damping should not be given an interpretation beyond that intended by the authors. The test was made simply to determine how much of the air resistance on the 7¾-in. plate might distort the measurements of the damping effect of the carefully calibrated friction induced by a simulated deck action. The air resistance measured was applied to an abnormally narrow deck and, of course, neglects the atmospheric damping on the truss members. With these and other limitations in mind, it is interesting to analyze the plotted atmospheric decrement as revealed by the difference between the two lower curves of Fig. 18.

It is noted that δ_a, the atmospheric decrement, approaches zero at zero amplitude and increases roughly in proportion to the amplitude. By correlating the curves of Figs. 18, 13*c*, and 14, the approximate equation for the logarithmic decrement in terms of the amplitude, η, is:

$$\delta_a = 0.001 + 0.0024\,\eta \qquad (32)$$

The second term is dominant except for small amplitudes. This seems characteristic of atmospheric damping, indicating that the principal resistance is a force varying as the square of velocity. The maximum value of the velocity of the vibration is $\omega\,\eta$, in which ω is the circular frequency of the vibration. The force will then be $C_1\,\omega^2\,\eta^2$, and in one cycle it will perform work equal to:

$$\Delta W = C_2\,\omega^2\,\eta^3 \qquad (33)$$

The energy of vibration, equal to the maximum value of the kinetic energy, is:

$$W = \frac{m\,v^2}{2} = \frac{m\,\omega^2\,\eta^2}{2} \qquad (34)$$

Hence,

$$\psi = \frac{\Delta W}{W} = \frac{C_2\,\omega^2\,\eta^3}{m\,\omega^2\,\eta^2/2} = \frac{C\,\eta}{m} \qquad (35)$$

If the air resistance were viscous, varying as the first power of the velocity, then Eq. 33 would be:

$$\Delta W = C_2\,\omega\,\eta^2 \qquad (36)$$

and Eq. 35 would be:

$$\psi = \frac{C}{m\,\omega} \qquad (37)$$

Thus Eqs. 37 and 35 represent, respectively, the first and second terms of Eq. 32. Atmospheric damping seems to be predominantly the result of the inertial force of the wind with a small constituent of viscous damping.

The fact that m is in the denominator of both Eqs. 35 and 37 is important. It means, for example, that if a bridge of the same shape is doubled in weight (without altering the frequency of vibration), δ_a will be reduced by half. A model test will indicate the atmospheric damping of a prototype only if the total weight, or weight per panel is scaled to the cube of the linear scale. In these tests the dead load on the truss model was selected simply to correlate with tests on the H-beam. It, of course, was not intended as an aerodynamic model of any prototype. Its weight is roughly three times too great for a typical truss bridge at a scale of 1 to 30, and seven times too great if interpreted at a scale of 1 to 50. Its stiffness also exceeds that of an aerodynamic model.

Fig. 24 shows the result of tests on a model of the proposed Tacoma Narrows Bridge with slotted deck for the purpose of isolating the atmospheric damping in vertical motion. Since this was an aerodynamic model of proper scale, it

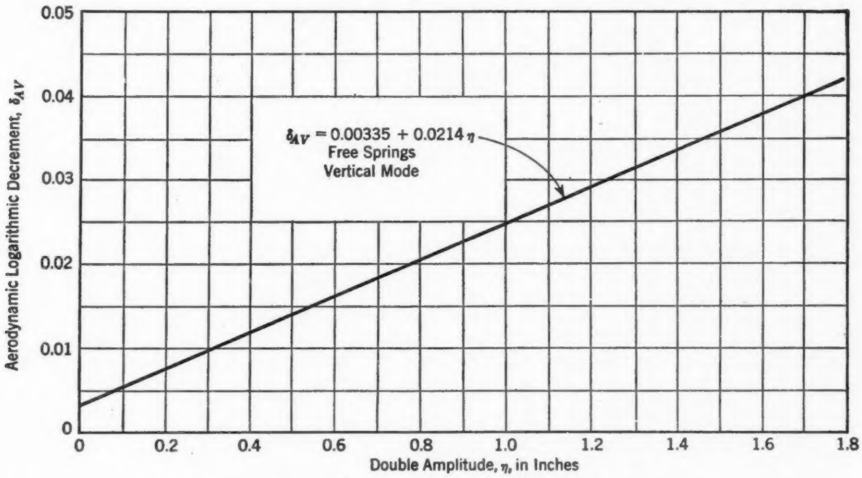

FIG. 24.—ATMOSPHERE DAMPING IN VERTICAL MOTION—TACOMA NARROWS BRIDGE PROPOSED DESIGN

will represent the atmospheric damping of the prototype if the abscissa scale is replaced by corresponding prototype amplitudes. It shows the effect of small viscous damping combined with that of a much greater damping arising from the dynamic pressure of the wind.

Fig. 25 shows curves for logarithmic decrement in still air for several modes of a 163-ft suspension bridge with unloaded backstays supporting a 3-ft wide plank walkway. Most of these curves show the typical form revealed by theory, as illustrated by Fig. 9, and by tests, as illustrated by the upper curve of Fig. 18. The curve in Fig. 25(*b*) illustrates strong Coulomb friction damping associated with the pronounced longitudinal motion of the suspended structure in the 1-node vertical mode. Possibly finer measurements would reveal a downward hook of the curve at low amplitude, but the increasing friction damping stifled the oscillation too rapidly to permit measurement at lower amplitude.

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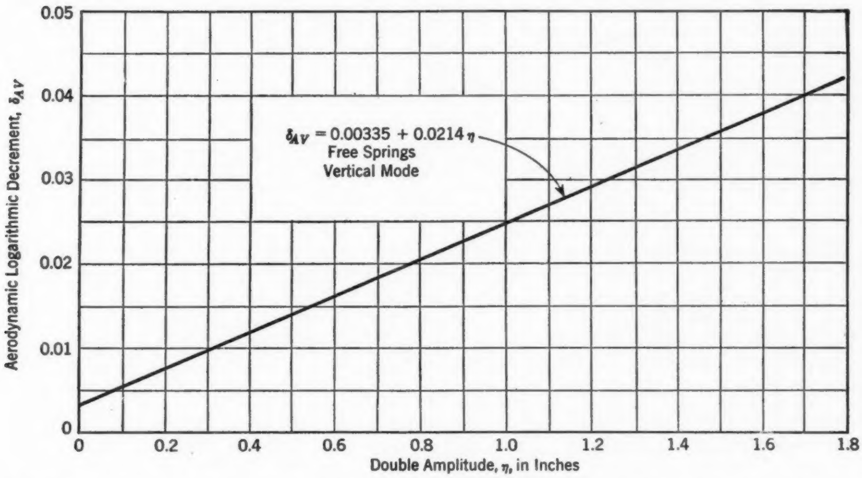

Fig. 24.—Atmosphere Damping in Vertical Motion—Tacoma Narrows Bridge Proposed Design

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It was found that one of the flat plate section models tested in the laboratory represented quite well a 1/3 scale model of the deck of the Twin Creeks Bridge (Wash.), and from the test data the atmospheric damping of the bridge was calculated for the 2-node vertical mode, shown in Fig. 25(*a*). The dashed curve represents the true structural damping, and the interval between the curves represents the atmospheric damping. Again, the characteristic variation is observed.

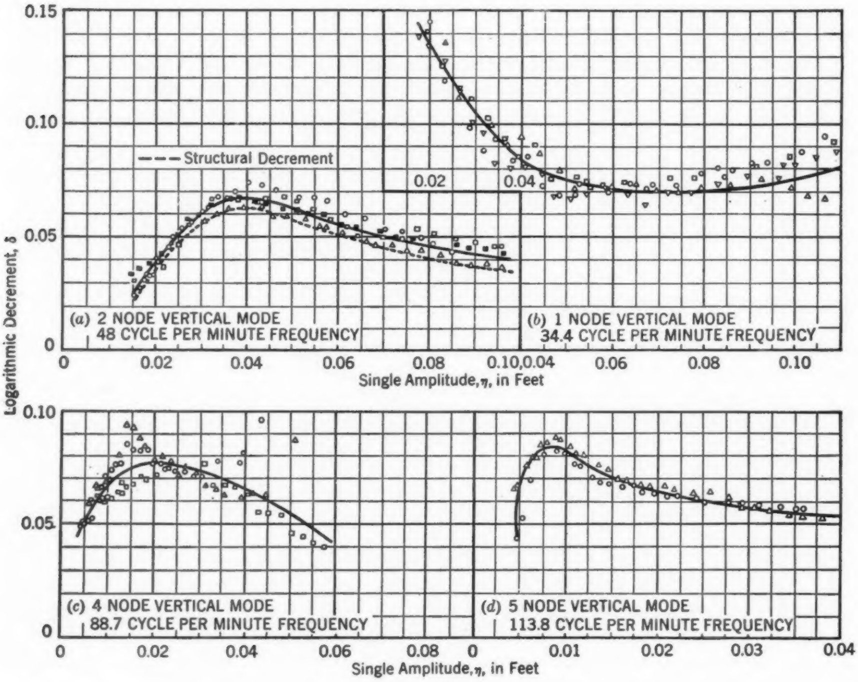


FIG. 25.—LOGARITHMIC DECREMENT IN STILL AIR FOR TWIN CREEKS BRIDGE

The damping of a light timber-decked foot bridge is, of course, no indication of the damping of suspension bridges in general. The tests were made at the same time on a 270-ft single lane highway bridge with plank floor, which showed much higher damping, this being attributed to the articulation of the joints of a relatively deep timber stiffening truss. Arne Selberg of Trondheim, Norway, has reported tests made on a number of girder-stiffened suspension bridges in Norway[8] that had either concrete deck or timber flooring. The decrements generally lie between 0.05 and 0.15.

It is the writer's opinion that the reliable determination of the structural damping of suspension bridges will require at least a few tests in which suspension bridges of considerable size are mechanically oscillated in different modes

[8] "Dampening Effect in Suspension Bridges," by Arne Selberg, *Publications*, International Association for Bridge and Structural Engineering, Vol. 10, 1950, p. 183.

in order to measure the rate of decay of their vibration. The theoretical analysis and laboratory tests presented in this paper and the more detailed treatment of damping by Mr. Bleich[9] should make it possible to expand the indications from a few bridges to secure a reliable estimate of the damping of suspension bridges of various types.

Tests referred to in this discussion were made as a part of the cooperative research on the aerodynamic behavior of suspension bridges by the Bureau of Public Roads and the University of Washington at Seattle, Wash.

F. B. FARQUHARSON,[10] M. ASCE.—This paper performs a very useful function in bringing before the profession the fundamentals of the mechanism of damping on this type of structure. Of equal value are the theoretical studies and the laboratory investigations on simple structural components, which provide a background for the evaluation of the probable amount of damping to be anticipated in various structural combinations.

It will be the purpose of this discussion to place on record certain additional laboratory data that will demonstrate, in connection with two different types of suspended structure, the nature of the beneficial effect of increase in total damping. In these tests the damping is expressed in terms of

$$\delta_{wo} = \delta_s + \delta_a \qquad (38)$$

in which δ_s equals the structural decrement, δ_a equals the atmospheric decrement and δ_{wo} is the total decrement obtained by oscillating the model in a given mode in still air.

The evaluation of δ_s of the model requires that the model be removed from the spring suspension and replaced by streamlined weights of negligible air resistance. In this type of suspension all of the structural damping arises in the spring suspension since the model is rigid. Since neither δ_s nor δ_a are of any direct interest at this point, it is usual to make comparisons in terms of their sum, δ_{wo}.

The two sets of curves in Fig. 26 are taken from extensive tests on a 1/50 scale section model of the original Tacoma Narrows Bridge. In the interest of simplification the data are presented in prototype terms with the wind scale representing velocity in the field in miles per hour.

In Fig. 26(*a*) the restricted vertical mode has been investigated under conditions in which δ_{wo} was varied in eight steps between 0.1077 and 0.0278. It is evident that alteration in damping has a negligible effect on the critical velocity but that the effect on maximum amplitude is very marked. An increase in logarithmic decrement from $\delta_{wo} = 0.0278$ to $\delta_{wo} = 0.1077$—a 3.88 fold increase—resulted in a 3.4 fold decrease in amplitude.

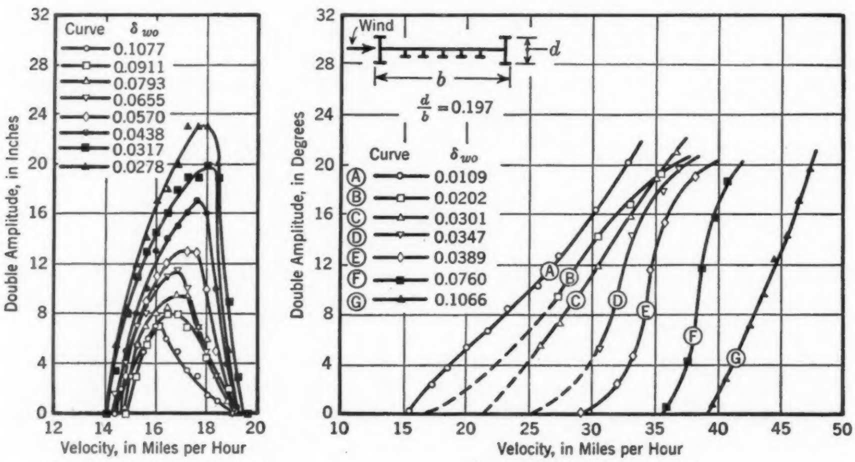
In Fig. 26(*b*) torsional response curves are presented under 7 conditions of damping in which δ_{wo} varied between 0.0109 and 0.1066. Here it is clear that the critical velocity in these catastrophic response curves is highly sensitive to

[9] "The Mathematical Theory of Vibration in Suspension Bridges," by Friedrich Bleich, C. B. McCullough, Richard Rosecrans, and George S. Vincent, U. S. Bureau of Public Roads, Government Printing Office, Washington D. C., 1950, Chapter VI.

[10] Prof., Civ. Eng.; Director, Eng. Experiment Station, Univ. of Washington, Seattle, Wash.

any change in level of damping. A 9.8 fold increase in the value of δ_{wo} corresponded to a 2.5 fold increase in critical velocity.

The data shown in Fig. 26(*b*) are taken from a very complete study of the effect of damping on the torsional mode for this section and has been somewhat simplified for this discussion through the elimination of another appearance of the same torsional mode (that appears at the same frequency). On this type of section the first appearance of the torsional mode (that is restricted or noncatastrophic) is completely suppressed by values of logarithmic decrement in excess of $\delta_{wo} = 0.039$. Below $\delta_{wo} = 0.035$ it becomes difficult to separate the catastrophic manifestation from the restricted, and the dashed portion of the curves B, C, and D represent a simplifying rationalization yielding a fair approximation of the catastrophic response.



(*a*) VERTICAL MODE, $N = 18.1$ CYCLES PER MINUTE

(*b*) TORSIONAL MODE, $N = 16.4$ CYCLES PER MINUTE

FIG. 26

In summary, it may be stated with respect to a girder-stiffened section that increase in damping is effective on restricted modes only in decreasing the amplitude, although in the catastrophic modes an increase in damping is effective in elevating the critical velocity of the response.

An additional example is shown in Fig. 27 and is taken from tests on the new Tacoma bridge in which stiffening was accomplished by means of a truss.[11] The principal improvement arising with this section, as compared with the original girder-stiffened section, was in the complete elimination of the vertical modes and the alteration of the catastrophic torsional response to a restricted form.

This restricted torsional response reacted to change in damping in exactly the same manner as did the vertical modes shown in Fig. 26(*a*). In Fig. 27 the logarithmic decrement was varied between values of $\delta_{wo} = 0.0152$ and

[11] "Unusual Design Problems—Second Tacoma Narrows Bridge," by Charles E. Andrew, *Transactions*, ASCE, Vol. 114, 1949, p. 955.

$\delta_{wo} = 0.0365$, a 2.4 fold increase. This increase in damping resulted in 11.4 fold reduction in amplitude, and increasing the damping to $\delta_{wo} = 0.05$ resulted in the complete elimination of all motion.

It may be stated, in general, that such increases in Coulomb damping as may be realized by the author's method are chiefly significant in controlling or eliminating a restricted type of oscillation. This fact is well illustrated in Fig. 27 in which the restricted torsional response was completely controlled by a relatively moderate increase in damping. On the other hand, Fig. 26(*b*) is typical of the behavior of a section subject to a catastrophic response in which no reasonable increase in damping can be expected to increase the critical velocity to a tolerable level.

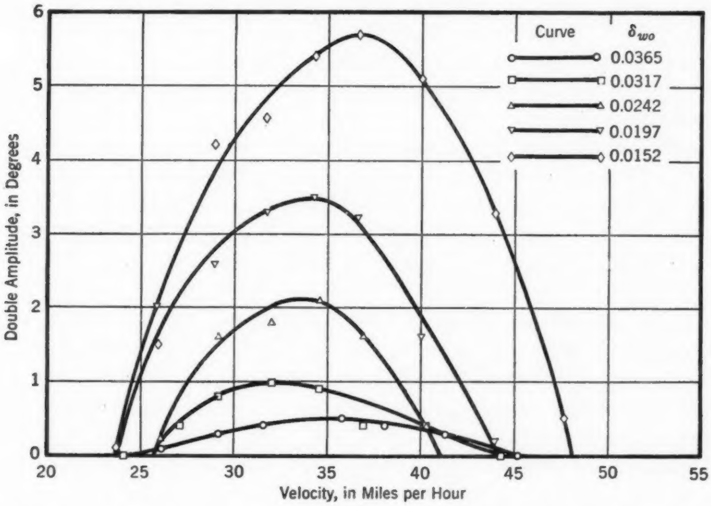


FIG. 27.—VARIATION OF AMPLITUDE IN THE TORSIONAL MODE; N = 14.6 CYCLES PER MINUTE AND ANGLE OF ATTACK = + 10 DEGREES

This paper serves to emphasize again the need for a determination of the structural damping existing on certain representative suspension bridges. Until such information is available, it will be impossible to fully analyze the behavior of these structures in wind, and reliable prediction regarding proposed bridges will be difficult.

The tests from which the data in this discussion were taken were made in the Structural Research Laboratory at the University of Washington, Seattle, at the request of the Washington Toll Bridge Authority and the Advisory Board on the Investigation of Suspension Bridges under a cooperative agreement with the Bureau of Public Roads.

ARNE SELBERG[12].—Since the writer is concerned with the same problem, this paper was of great interest to him. However the tests he conducted

[12] Prof., Institutt for Statikk, Norges Tekniske Høgskole, Trondheim, Norway.

were on full-sized suspension bridges with spans varying from 230 to 525 ft.[13] The results of these tests are in agreement with those of the paper. For vertical oscillation with 1 node the observed values of the decrement δ varied in value from 0.07 to 0.16 for bridges with rolled steel beam stiffening girders and continous reinforced concrete slab. For bridges with timber flooring, the value of δ was between 0.12 and 0.22. Vertical oscillation with 2 nodes had δ values varying from 0.04 to 0.08 and 0.07 to 0.185 for the same bridges.

The different values in δ are the result of frictional forces in action in bearings, suspenders, and other components, as a result of the longitudinal movements in the bridge for 1-node oscillation.

For torsional oscillation, the values of δ were between 0.185 and 0.05; for oscillation with 1 node, between 0.2 and 0.3; and for 2-nodes vibration, from 0.06 to 0.12 and 0.15 to 0.18. The tests show that timber flooring gives a high value of δ because of the internal frictional forces in the flooring. With continuous concrete flooring the frictional forces are of lesser importance, and, for some types of oscillations, dampening will be mainly the result of internal or hysteresis dampening.

As reinforced concrete is an important part of the suspended span in many suspension bridges, the writer is of the opinion that tests on the internal dampening in concrete slabs are of great interest and should be made in order to complete the investigation in the paper. However, tests with reinforced concrete slabs must also include torsional oscillations.

THE LATE FRIEDRICH BLEICH,[14] M. ASCE, and L. W. TELLER,[15] M. ASCE.—The discussions that have been presented are all contributions to the subject of the paper. The general approval of the paper by these discussers is particularly gratifying because of the intimate knowledge each has of the subject of structural damping.

The comparisons offered by Mr. Bernhard between his own experience in damping tests of full-size structures and certain observations reported in the paper indicate a good correlation.

Mr. Vincent is quite right in cautioning against attempts to extend the interpretation of the data on atmospheric damping, as given in the paper, beyond that intended. His analysis of the atmospheric component of the over-all damping observed for the truss is an interesting addition. The data obtained in the experiments with the 163-ft suspension bridge are interesting. The need for data on the damping characteristics of suspension bridges obtained from tests on full-size structures is quite apparent as Mr. Vincent points out. The conduct of such tests involves practical problems of some magnitude, however, and means for solving these problems satisfactorily are not yet available.

The laboratory data and the discussion of them offered by Mr. Farquharson are both interesting and enlightening. Damping tests with full-size suspension bridges, when they are made, will afford an opportunity for many useful com-

[13] "Dampening Effect in Suspension Bridges," by Arne Selberg, *Publications*, International Association for Bridge and Structural Eng., Vol. 10, Zurich, 1950, p. 183.

[14] Formerly with Frankland and Lienhard, Cons. Engrs., New York, N. Y. (Mr. Bleich died on February 17, 1950.)

[15] Prin. Highway Engr., U. S. Bureau of Public Roads, Washington, D. C.

parisons with the damping data on full models obtained in the comprehensive studies conducted at the University of Washington, Seattle, Wash.

The comparisons offered by Mr. Selberg as the result of his tests on a number of suspension bridges of moderate span in Norway are of interest. It is true, as Mr. Selberg points out, that tests of the internal damping characteristics of reinforced concrete slabs would have made a useful addition to the test program described in the paper.

* Deceased.